

# **Thermoelectric Module with Thin Film Substrates**

This application claims the benefit of US Provisional Patent Application No. 60/304,898, filed July 12, 2001.

## **5 BACKGROUND OF THE INVENTION**

### **1. Field of the Invention**

The present invention relates generally to thermoelectric devices. Particularly, the present invention relates to thermoelectric devices and a method of fabricating the same.

### **2. Description of the Prior Art**

Many types of industrial equipment require cooling or heating during their operation. Typical examples include semiconductor process equipment, pharmaceutical and biotechnology fermentation/separation vats, machine tools, air conditioners, plastic molding/extrusion equipment, analytical equipment, welding equipment, lasers, etc. One common way to provide the required cooling or heating is with a re-circulating coolant temperature control unit or chiller. A typical chiller consists of a Freon-based refrigeration loop connected to a recirculating coolant loop via a heat exchanger. However, as the world community becomes increasingly concerned about ozone depletion and global warming, a replacement for the

standard Freon-based refrigeration technology is needed. Thermoelectric technology offers a clean, environmentally friendly, solid state alternative.

Thermoelectric cooling was first discovered by Jean-Charles-Athanase Peltier in 1834, when he observed that a current flowing through a junction between two

5 dissimilar conductors induced heating or cooling at the junction, depending on the direction of current flow. This is called the Peltier effect. Practical use of thermoelectrics did not occur until the early 1960s with the development of semiconductor thermocouple materials, which were found to produce the strongest thermoelectric effect. Most thermoelectric materials today comprise a crystalline alloy of bismuth, tellurium, selenium, and antimony.

10 Thermoelectric devices are solid-state devices that serve as heat pumps. They follow the laws of thermodynamics in the same manner as mechanical heat pumps, refrigerators, or any other apparatus used to transfer heat energy. The principal difference is that thermoelectric devices function with solid state electrical components as compared to more traditional mechanical/fluid heating and cooling components.

15 The circuit for a simple thermoelectric device generally includes two dissimilar materials such as N-type and P-type thermoelectric semiconductor elements. The thermoelectric elements are typically arranged in an alternating N-type element and

20 P-type element configuration. In many thermoelectric devices, semiconductor materials with dissimilar characteristics are connected electrically in series and thermally in parallel. The Peltier effect occurs when the voltage is applied to the N-

type elements and the P-type elements resulting in current flow through the serial electrical connection and heat transfer across the N-type and P-type elements in the parallel thermal connection.

- Typical construction of a thermoelectric module consists of electrically
- 5 connecting a matrix of thermoelectric elements (dice) between a pair of electrically insulating substrates. The operation of the device creates both a hot-side substrate and a cool-side substrate. The module is typically placed between a load and a sink such as liquid plates, surface plates, or convection heat sinks. The most common type of thermoelectric element is composed of a bismuth-tellurium ( $\text{Bi}_2\text{Te}_3$ ) alloy. The
- 10 most common type of substrate is alumina (96%). These typically range in thickness from about 0.010 inches (0.25 mm) to about 0.040 inches (1.0 mm). A description of conventional thermoelectric modules and technology is also provided in the *CRC Handbook of Thermoelectrics and Thermoelectric Refrigeration* by H. J. Goldsmid.

A typical thermoelectric device requires DC power in order to produce a net

15 current flow through the thermoelectric elements in one direction. The direction of the current flow determines the direction of heat transfer across the thermoelectric elements. The direction of net, non-zero current flow through the thermoelectric elements determines the function of the thermoelectric device as either a cooler or heater.

20 U.S. Patent No. 6,222,243 (2001, Kishi et al.) discloses a thermoelectric device comprising a pair of substrates each having a surface, P-type and N-type thermoelectric material chips interposed between the pair of substrates, electrodes

disposed on the surface of each substrate and connecting adjacent P-type and N-type thermoelectric material chips to each other, and support elements disposed over the surface of each of the substrates for supporting and aligning the thermoelectric material chips on the respective electrodes between the pair of

5 substrates. Each of the thermoelectric material chips has a first distal end connected to one of the electrodes of one of the substrates and a second distal end connected to one of the electrodes of the other of the substrates. The adjacent P-type and N-type thermoelectric material chips connected by the electrodes are interposed between the pair of substrates such that a line connecting centers of the adjacent P-type and N-type thermoelectric material chips is coincident with a diagonal of each of the adjacent P-type and N-type thermoelectric material chips. The substrate used in the Kishi et al. device is a silicon wafer. A disadvantage of using silicon wafers as a substrate is the brittleness of the wafer and the thermal stresses that occur at the junction of the substrate and the thermoelectric material chips.

10 15 U.S. Patent No. 5,362,983 (1994, Yamamura et al.) discloses a thermoelectric conversion module with series connection. The thermoelectric conversion module is constituted by either rows of thermoelectric semiconductor chips or columns of thermoelectric semiconductor chips of the same type. This arrangement improves assembling workability as well as preventing erroneous arrangement. The substrate  
20 used in the Yamamura et al. device is a ceramic substrate. A disadvantage of using a ceramic substrate is the brittleness of the ceramic and the thermal stresses that occur at the junction of the substrate and the thermoelectric semiconductor chips.

- Other disadvantages of current thermoelectric module technology require that the substrates be thick enough to withstand cracking. The thicker the module, the heavier the thermoelectric module becomes. Also material costs for the thicker substrates are higher. In addition, the use of silicon or ceramic substrates limits the
- 5 size and shape of thermoelectric modules. For instance, should spacing requirements determine that a normal 0.025 inch (0.64 mm) boundary between the edge of a pad and the edge of the module is too large, a special abrasive process must be used to reduce the boundary. Due to its brittleness, this may lead to chipping of the ceramic substrate.
- 10 Also, the rigidity of the ceramic substrate and the thermal cycling of a thermoelectric module where the heating side of the module is trying to expand while the cooling side of the module is trying to contract cause a "Potato Chip Effect." This Effect puts stresses on the thermoelectric chips and results in the eventual failure at the junctures between different mediums. These stresses increase as the module size increases. Furthermore, current thermoelectric module technology limits the available applications where these devices can be used. For instance, current thermoelectric module technology is not practical in applications having irregular and non-flat surfaces.
- 15 Therefore, what is needed is a thermoelectric module that is thinner than currently available thermoelectric modules. What is also needed is a thermoelectric module that can be used in applications having irregular and non-flat surfaces. What

is further needed is a thermoelectric module that can be shaped and sized to fit the application.

## SUMMARY OF THE INVENTION

5 It is an object of the present invention to provide a thermoelectric module that is thinner than currently available thermoelectric modules. It is another object of the present invention to provide a thermoelectric module that can be used in applications having irregular and non-flat surfaces. It is still another object of the present invention to provide a thermoelectric module that can be formed to odd shapes and  
10 10 to provide a way to make much larger devices than heretofore possible. It is yet another object of the present invention to provide a thermoelectric module with thin, flexible substrates.

The present invention achieves these and other objectives by providing a thermoelectric module with a flexible thin film substrate on one or both sides of the  
15 15 module. The thin film substrate provides the electrical connection between the P-type and N-type thermoelectric elements and the electrical isolation from the heat source or heat sink. The thin film substrate also functions as a heat transfer medium. A material for use as a thin film material is one that preferably has relatively good heat transfer, a broad operating temperature range, relatively high dielectric  
20 20 strength, and relatively high resistance to thermal cycling fatigue. An example of an acceptable material for use as a thin film material is polyimide. Other thin film

materials with similar properties may also be used. An example of such a material is an epoxy-based film.

The thin flexible film is laminated or otherwise bonded to copper or other electrically conductive material. An example of ways to bond or laminate copper to

5 the thin, flexible film include sputtering a conductive material onto the surface or using adhesives to bond the copper material to the surface. The electrically conductive material forms the electrical junction between the semiconductor elements of the module. The thin film material also provides electrical isolation between the electrical connections and the heat source or heat sink.

10 An external layer of thermally conductive material to enhance heat transfer between the thermoelectric module and a heat source or heat sink is typical but not necessary. The external layer is also laminated to or otherwise bonded to the opposite surface of the thin film substrate. The external, thermally conductive material may cover the entire outside surface of the thin film substrate, or it may

15 mirror the electrical connection pads forming the junction between the semiconductor elements of the thermoelectric module.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIGURE 1 is a cross-sectional view of the present invention showing the

20 arrangement of the thermoelectric elements between flexible substrates.

**FIGURE 2** is an enlarged, cross-sectional view of a portion of the present invention showing the different components of the thermoelectric module with flexible substrates.

- 5   **FIGURE 3** is a top view of the present invention showing a large thermoelectric module using flexible substrates.

#### **DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT**

The preferred embodiment(s) of the present invention is illustrated in Figs. 1-  
10   3. Figure 1 is a side view of a thermoelectric device **10** according to the present  
invention. The basic structure of thermoelectric device **10** comprises P-type  
thermoelectric elements **14** and N-type thermoelectric elements **16** sandwiched  
between flexible substrates **12** and **13**. P-type thermoelectric elements **14** and N-  
type thermoelectric elements **16** are electrically connected in series and thermally  
15   connected in parallel to provide the Peltier effect, which is the technological basis for  
a working thermoelectric module. It is noted that only one side of thermoelectric  
device **10** may use the thin, flexible substrate while the other side uses traditional  
substrates, i.e. ceramic (alumina) or silicon. When using only one thin, flexible  
substrate, it is preferable to use the flexible substrate on the hot side of the  
20   thermoelectric module. The hot side tends to incur larger thermal stress due to the  
larger temperature difference that occurs during thermal cycling. The flexible

substrate allows for expansion and contraction with much less restraint and stress because of its flexible nature.

Flexible substrates **12** and **13** are made of a flexible, thin film material. The thin film material provides electrical isolation from a heat source or heat sink while 5 also functioning as a heat transfer medium. In particular, the material should have relatively high resistance to thermal cycling fatigue, relatively high dielectric strength, a broad operating temperature range, and relatively good heat transfer characteristics. The preferred material used in the present invention is a polyimide sheet material having a thickness of about 0.0005 inch (0.01 mm) to about 0.002 10 inch (0.051 mm). Other usable materials include thin-film epoxies and materials that meet the particular specifications required for a given application. Although the thickness of the flexible thin film material will enhance certain material characteristics at the expense of other material characteristics, the general criteria for selecting a preferred thickness for flexible substrates **12** and **13** is the material's tensile strength, 15 its durability to withstand shear stress relative to the weight of the thermoelectric elements, its thermal conductivity, i.e. its ability to transfer heat, and its ability to withstand thermal stresses associated with thermal cycling of thermoelectric devices.

P-type thermoelectric elements **14** transfer heat in the direction of the current and N-type thermoelectric elements **16** transfer heat in the reverse direction of the 20 current. By alternating P-type and N-type thermoelectric elements **14** and **16**, hot and cold junctions are formed when electric current is provided to thermoelectric device **10**. A heat exchanger (not shown) is thus configured so that heat may either

be removed from, or added to, the heat exchanger by merely changing the direction of current flowing through thermoelectric device 10. Conversely, establishing a differential temperature across the thermoelectric device 10 will result in the generation of Direct Current at a level that is dependent on both the physical design 5 of the module and the magnitude of the differential temperature. Thermoelectric materials most commonly used for making P-type thermoelectric elements 14 and N-type thermoelectric elements 16 are composed of a bismuth-tellurium alloy.

Turning now to Figure 2, there is illustrated an enlarged side view of a selected portion of Fig. 1 to show the detail of thermoelectric device 10.

10 Thermoelectric device 10 includes P-type and N-type thermoelectric elements 14 and 16, respectively, sandwiched between thin film, flexible substrates 12 and 13. Although a flexible substrate on each side of the P-type and N-type thermoelectric elements 14 and 16 is illustrated, a thermoelectric device 10 may have a flexible substrate on only one side, as previously discussed. Each distal end of P-type and 15 N-type thermoelectric elements 14 and 16 are coated with a diffusion barrier 18. Diffusion barrier 18 prevents diffusion/migration of copper into P-type and N-type thermoelectric elements 14 and 16. Diffusion/migration of copper into the thermoelectric elements 14 and 16 shortens the working life of these components as 20 thermoelectric elements, which may be acceptable in applications where the cost of the thermoelectric module is a determining factor. In these types of applications, diffusion barrier 18 is not required. Materials generally acceptable as diffusion

barrier materials are nickel, or a titanium/tungsten mix, or molybdenum. The preferred material used in the present invention is nickel.

Flexible substrates **14** and **16** are coated with, laminated with, or otherwise bonded with a layer of an electrically conductive material, preferably copper, to form

5      electrically conductive pads **20**. The electrically conductive material may be formed over the entire surface of flexible substrates **12** and **13**, which is then subsequently etched into the desired electrical connection pad pattern with the excess conductive material removed, or the desired connecting pad pattern may be coated, laminated or otherwise bonded to flexible substrates **12** and **13** in the desired configuration.

10     P-type and N-type thermoelectric elements **14** and **16** are preferably soldered to the electrically conductive pads in series forming a sandwiched matrix. Electrically conductive epoxy is another form of electrically conductive material that may also be used to form the desired conductive pads connecting the P-type and N-type thermoelectric elements **14** and **16** in series. On the opposite surface of flexible substrates **14** and **16**, mirror-image pattern of pads **22** of the electrically conductive material pads **20** may be provided to enhance thermal conductivity between thermoelectric device **10** and a surface with which thermoelectric device **10** is in contact. Alternately, thermally conductive epoxy may be used to form the desired pads **22** on the outside surfaces of flexible substrates **12** and **13**.

20     Although the diffusion barrier **18** was described as being applied to the distal ends of the P-type and N-type thermoelectric elements **14** and **16**, it is noted that the

diffusion barrier **18** may instead be applied to the conductive pads **20** on the flexible substrates **12** and **13**.

Figure 3 shows a reduced, top view of an example of a thermoelectric device **10** that is larger than previously practical with conventional module construction. Fig. 5 illustrates a thermoelectric device **10** having an eight (8) inch (20.32 cm) diameter and a module thickness of about 0.100 inch (2.54 mm).

A method of making a thermoelectric device **10** includes using a thin, flexible sheet material having an electrically conductive coating on both sides. Such substrate is available under the tradename/trademark GOULDFLEX available from Sheldahl, Inc., Northfield, MN. The substrate generally has a copper coating on both sides with a coating thickness of about 0.0028 inch (0.071 mm). The desired pattern of electrically conductive pads is etched onto the substrate using known masking techniques. The copper of the conductive pad pattern is then pre-tinned to prepare the surface for soldering the dice (P-type elements **14** and N-type elements **16**) thereto. Thermocouple semiconductor material ( $\text{Bi}_2\text{Te}_3$  alloy) appropriate for forming P-type thermoelectric elements **14** and N-type thermoelectric elements **16** is cut to the desired size. The size of the P-type and N-type elements depends on the heat pump capacity needed for the thermoelectric device **10**, which can be easily determined by those skilled in the art.

20 The ends of each P-type and N-type element are bonded with a diffusion barrier **18**, preferably nickel. To reduce the cost of making a thermoelectric device **10**, the diffusion barrier step may be eliminated. However, it should be understood

- that the useful life of the thermoelectric device 10 would be shortened because of copper migration into the P-type and N-type elements 14 and 16. The P-type and N-type thermoelectric elements 14 and 16 are then attached, preferably by soldering, to the pre-tinned, electrically conductive pads 20 of the flexible substrate 12 by
- 5 manually picking and placing the P-type and N-type elements on the substrate, preferably using an alignment grid or screen, or by using an automated system that performs the placement and alignment and soldering, or by using a semi-automated pick and place system that solders the components. A second substrate 13 is attached to the opposite ends of the P-type and N-type elements in a similar manner.
- 10 The second substrate 13 may also be a thin, flexible substrate or it may be the conventional ceramic substrate.
- It was discovered that to obtain a flexible substrate thermoelectric device 10 having performance characteristics equal to or better than the performance characteristics of ceramic-based substrate thermoelectric modules, the electrically
- 15 conductive material forming the conductive pads 20 must have a thickness greater than the thickness of conductive coatings currently available on flexible substrates. Current conductive coating thickness is capable of supporting 4 amp thermoelectric modules. The thickness of the electrically conductive material is dependent on the desired heat pump capacity of the thermoelectric device 10, the size of the
- 20 thermoelectric device 10, and the size of the P-type and N-type thermoelectric elements used in the thermoelectric device 10. A thicker electrically conductive coating is desired to enable greater power densities, which results in greater heat

pumping capacities for any given area. In general, design conductor cross-sections should be in accordance with those referenced in Mil Standard 275E.

However, the conductive layer thickness on currently available flexible substrates cannot be used to make thermoelectric modules capable of using 6 to 15 5 amps of current, which require a conductive layer thickness equal to or greater than 0.003 inch (0.076 mm) and typically in the range of 0.008 inch (0.20 mm) to 0.015 inch (0.38 mm). The preferred thickness is 0.012 inch (0.30 mm).

It was also discovered that producing a flexible substrate having the thicker 10 conductive pads 20 for making a 6 amp to 15 amp thermoelectric module was a problem. Conventional wisdom by those skilled in the art of disposing conductive layers onto flexible substrates was that the thicker layers could not be done using 15 current, state-of-the-art procedures. A variety of processes were developed to obtain a flexible substrate having the required characteristics for use in a flexible substrate thermoelectric module with current density ratings of 6 to 15 amps, depending on the application. Electrically insulating substrates with thicker conductive coatings are available from Ferrotec USA, Nashua, NH.

Using flexible substrates 12 and 13, several advantages are obtained with the present invention over the prior art. Relatively large thermoelectric modules can now be made that previously were impractical. The present invention provides the ability 20 to make flexible thermoelectric modules that follow the contour of a shaped surface, thus making thermoelectric modules a viable alternative for applications that have irregular and/or non-flat surfaces. Use of a thin, flexible film substrate in a

thermoelectric module reduces the overall weight of a thermoelectric module and reduces manufacturing costs. Because thermoelectric modules are generally used in applications that turn the thermoelectric module on and off, the use of a thin, flexible film substrate increases cycling life of the thermoelectric module. The

- 5 flexibility of the substrate reduces the overall stresses caused by thermal cycling. In addition, the reduced thickness of a thermoelectric module made in accordance with the teachings of the present invention provides new application opportunities that were not practical for existing thermoelectric module technology. Also, the present invention provides one with the ability to create thermoelectric modules having odd  
10 shapes that was impractical using conventional module construction techniques.

Although the preferred embodiments of the present invention have been described herein, the above description is merely illustrative. Further modification of the invention herein disclosed will occur to those skilled in the respective arts and all such modifications are deemed to be within the scope of the invention as defined by  
15 the appended claims.